Project Report
LSP-132

White Light Heterodyne Interferometry SNR

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LEXINGTON, MASSACHUSETTS

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ABSTRACT

White light heterodyne interferometry is a powerful technique for obtaining high-angular resolution information of astronomical objects, and avoids some of the technical challenges of direct detection interferometry. However, it suffers a significant SNR penalty. This paper derives the SNR equations for heterodyne interferometry and compares its performance to a direct detection interferometer in the visible through LWIR wavelength range. Relative performance for imaging deep space, solar-illuminated objects is discussed.

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1. INTRODUCTION

The subject of heterodyne interferometry, most successfully demonstrated for astronomy in the long-wave infrared (LWIR) at the Berkeley Infrared Spatial Interferometer (ISI) from the mid-1980s onward [Hale], has recently been discussed as a possible approach to the more generalized ground-based, high-resolution imaging problem (see Ireland and Monnier, for example). Heterodyne interferometry is particularly attractive as the community considers large interferometers taking advantage of many apertures, because the heterodyne approach obviates the need to route the very faint science light from the many apertures to a common location for beam combining, and the continual progress in high-speed detectors and digitizers has steadily increased the optical bandwidth over which the measurements can be made. For a many-aperture system, the heterodyne approach has the particular advantage that all "N-choose-two" combinations can be measured at the signal-to-noise ratio (SNR) determined by the single-aperture photon flux, without either having to split the light N – 1 ways or take the extra shot-noise penalty from Fizeau beam combining light from all apertures together.

Heterodyne interferometry has been shown to be competitive in sensitivity for astronomical sources that emit brightly over a narrow bandwidth in the LWIR, as direct detection (also called homodyne) interferometers suffer from sensitivity to the thermal background at these wavelengths. However, while it offers significant system simplification, the heterodyne approach can never come near the sensitivity of traditional direct detection interferometers in the visible- and near-IR, where shot-noise-limited detectors are available. In the LWIR, the advantage of a direct detection interferometer over a single-channel heterodyne system is still several hundred, but the performance becomes comparable if a many-channel heterodyne system is considered.

2. HETERODYNE INTERFEROMETRY SNR

The sensitivity of a heterodyne interferometer is fundamentally different from that of a direct detection interferometer, or even from that of a heterodyne laser radar [Shapiro], because of the unique coherence properties of white light and because the phase measurement architecture requires that two independent in-phase and quadrature (IQ) phasor measurements be multiplied together to obtain the science quantity, the interferometric phase.

The coherence time of white light is equal to the inverse of the optical bandwidth $\Delta\nu$ being measured (identically equal for a rectangular lineshape; the exact scale factor depends on the shape of the optical spectrum [Goodman, 168]). Conceptually, this means that the phase of white light relative to a stable phase reference (a local oscillator, or LO) will undergo a random phase slip on average once within a time $T_o = 1/\Delta\nu$. This does not make interferometry impossible, because the white light phase at every aperture undergoes the same phase slips, as the light has come from the same source. It does mean, however, that the phase of the white light relative to the LO must be measured at least as fast as the inverse optical bandwidth, and that these IQ phasor measurements at each aperture must be multiplied together at this rate before any integration. The product phasor, the angle of which is the true interferometric phase, can then be integrated up to the next longer coherence time (typically the atmospheric coherence time). This is shown mathematically in the subsequent expressions.

As stated, an IQ measurement must be made over a time T_o, the coherence time of the white light where $T_o = 1/\Delta\nu$. While the heterodyne signal would generally be placed on an intermediate frequency carrier, the optical measurement can be represented

$$|E_S + E_{LO}|^2 = |E_S|^2 + |E_{LO}|^2 + 2E_S E_{LO} cos\varphi$$

$$= \dot{n}_S T_o + \dot{n}_{LO} T_o + 2\sqrt{\dot{n}_S T_o\, \dot{n}_{LO} T_o} cos\varphi$$

where $\dot{n}_S$ is the detected rate of signal photons at one aperture in photons per second, $\dot{n}_{LO}$ is the LO photons per second, and ϕ is the relative phase between signal and LO fields. For the purpose of noise analysis, this can be conveniently represented in complex form:

$$z_1 = \sqrt{2\dot{n}_S T_o\, \dot{n}_{LO} T_o}\, \tilde{S}_1 + \sqrt{\dot{n}_S T_o}\, \widetilde{N}_1 + \sqrt{\dot{n}_{LO} T_o}\, \widetilde{M}_1$$

where $\tilde{S}_1 = e^{i\varphi}$ is a unity magnitude phasor of fixed angle, and $\widetilde{N}_1$ and $\widetilde{M}_1$ are unity-variance complex Gaussian random variables. (The factor of two under the radical comes from the mean square of the cosine.) From this expression, the conventional heterodyne SNR can be read off:

$$SNR_{Het} = \frac{2\dot{n}_S T_o\, \dot{n}_{LO} T_o}{\dot{n}_S T_o + \dot{n}_{LO} T_o} = \frac{2\dot{n}_S T_o}{1 + \dot{n}_S T_o / \dot{n}_{LO} T_o}$$

This is the appropriate SNR for phase estimation, where for large LO power, the variance of the phase estimate is the inverse of twice the number of detected signal photoelectrons (Kingston, ch. 3). The phasor (IQ) measurement z_1 is made at aperture 1 and the phasor measurement z_2 is made at aperture 2, but the interferometric phase is the phase difference between these quantities and must be calculated every T_o. The angle operation is effected by phasor multiplication by the complex conjugate:

$$z_1 z_2^* = 2\dot{n}_S T_o\, \dot{n}_{LO} T_o\, \widetilde{S_1}\, \widetilde{S_2^*} + \dot{n}_S T_o\, \widetilde{N_1}\, \widetilde{N_2^*} + \dot{n}_{LO} T_o\, \widetilde{M_1}\, \widetilde{M_2^*} + \dot{n}_S T_o \sqrt{2\dot{n}_{LO} T_o}\left(\tilde{S}_1\, \widetilde{N_2^*} + \tilde{N}_1\, \widetilde{S_2^*}\right)$$

$$+\, \dot{n}_{LO} T_o \sqrt{2\dot{n}_S T_o}\left(\tilde{S}_1\, \widetilde{M_2^*} + \tilde{M}_1\, \widetilde{S_2^*}\right) + \sqrt{\dot{n}_S T_o\, \dot{n}_{LO} T_o}\left(\tilde{N}_1\, \widetilde{M_2^*} + \tilde{M}_1\, \widetilde{N_2^*}\right)$$

where importantly $\widetilde{S_1}\, \widetilde{S_2^*}$ is an expectation value over time and is therefore equal to the visibility γ, which accounts for the degree of correlation along the particular baseline (Labeyrie, 45). Noting that $\sigma^2(NM) = 2\sigma^2(N)\sigma^2(M)$ and $\sigma^2(N+M) = \sigma^2(N)+\sigma^2(M)$, the SNR for this quantity can then be similarly read off:

$$SNR_{zz*} = \frac{4\gamma^2\, (\dot{n}_S T_o)^2\, (\dot{n}_{LO} T_o)^2}{2(\dot{n}_S T_o)^2 + 2(\dot{n}_{LO} T_o)^2 + 4(\dot{n}_S T_o)^2(\dot{n}_{LO} T_o) + 4(\dot{n}_S T_o)(\dot{n}_{LO} T_o)^2 + 4(\dot{n}_S T_o)(\dot{n}_{LO} T_o)}$$

$$SNR_{zz*} = \frac{4\gamma^2\, (\dot{n}_S T_o)^2}{2 + 4(\dot{n}_S T_o) + {2(\dot{n}_S T_o)^2}\big/{(\dot{n}_{LO} T_o)^2} + {4(\dot{n}_S T_o)^2}\big/{(\dot{n}_{LO} T_o)} + {4(\dot{n}_S T_o)}\big/{(\dot{n}_{LO} T_o)}}$$

$$SNR_{zz*} = \frac{\gamma^2\, (\dot{n}_S T_o)^2}{1/2 + (\dot{n}_S T_o)}$$

as all noise terms with $\dot{n}_{LO} T_o$ in the denominator will tend to zero for sufficient LO power. Because of the relatively short time T_o and narrow bandwidth of $1/T_o$ on an optical scale, $\dot{n}_S T_o$ is small in all cases of interest (see below), and the expression reduces to

$$SNR_{zz*} \cong 2\gamma^2\, (\dot{n}_S T_o)^2$$

Because the angle of the phasor $z_1 z_2^*$ is, unlike the angle of z_1 or z_2, constant in time up to the coherence time of the atmosphere, many $z_1 z_2^*$s can be repeatedly measured and integrated up, increasing the SNR by T_c / T_o. Therefore, noting that $\dot{n}_S = \frac{\eta P}{h\nu}\Delta\nu$, where P is the power per unit bandwidth at the receive aperture and η the system optical efficiency,

$$SNR_{zz*,Tc} = 2\gamma^2\, (\dot{n}_S T_o)^2 \left(\frac{T_c}{T_o}\right) = 2\gamma^2 \left(\frac{\eta P}{h\nu}\right)^2 \Delta\nu\, T_c$$

which is the expression in [Ireland and Monier, eq. 2], except that the visiblity is included as in [Hale]. This is also consistent with the expression in [Townes, eq. 3] for an integration time equal to the coherence time, allowing for the typographical error confusing root-mean-square and variance SNR in that reference. Note that in this notation, P is the optical power per bandwidth in Hz.

This is the SNR for phase estimation on a baseline of visibility gamma for an integration time equal to the atmospheric coherence time. If insufficient SNR is available in a single atmospheric coherence time, traditional methods of integration would be applied using this base SNR (for example, out-of-band fringe tracking [Hall], coherent integration [Jorgensen et al.], phase closure [Shao and Colavita], or wavelength-diversity approaches [Hutchin].

Finally, it is important to note that the maximum RF electrical bandwidth available is far less than the maximum optical bandwidth that can be used. The maximum fractional optical bandwidth that can be used for a single phase measurement is roughly the inverse of the number of linear resolution elements in the interferometric reconstruction. This is because any wider bandwidth would represent different effective baselines or different spatial frequencies, and therefore lead to blurring of the image. Asserting that the interferometric phase across an optical bandwidth Δν' is constant (as it would represent a single spatial frequency in the reconstruction), multiple heterodyne channels could be measured, each offset by Δν and spanning Δν'. In this way, the SNR for such a multichannel system would be expressed

$$SNR_{zz*,Tc,\Delta\nu'} = 2\gamma^2 \left(\frac{\eta P}{h\nu}\right)^2 \Delta\nu'\, T_c$$

where Δν' = N Δν, N the number of heterodyne channels. This would require a large number of phase-locked LOs, or a frequency comb or similar optical system.

A final note regarding the smallness of $\dot{n}_S T_o$: for $\dot{n}_S T_o$ equal to one, the power per unit bandwidth *P* at 1550 is 1.3×10^{-19} W/Hz. As a comparison, a very bright (V-band) magnitude zero sun-like star puts out 4×10^7 photons/s/m^2/nm at the surface of the earth at this wavelength, which corresponds to a power per unit bandwidth of 3.2×10^{-23} W/Hz in a 1-m aperture, a factor of 4,000 lower. So the approximation above for small $\dot{n}_S T_o$ is always justified for astronomical observation.

3. DIRECT DETECTION (HOMODYNE) SNR

For comparison, the SNR for phase estimation for a direct detection interferometer is reviewed. The advantage of the direct detection approach is that while the white light is only coherent with respect to a stable phase reference over a time equal to the inverse bandwidth, it is always coherent with itself. Light from the same target traveling along different paths through two separated apertures is coherent as long as the optical path lengths can be matched to within the coherence length of the bandwidth being measured (where the coherence length is defined $\ell_c = \lambda^2/\Delta\lambda$). The maximum fractional bandwidth that can be used for a single phase measurement is now much larger and limited to roughly the inverse of the number of linear resolution elements. As such, fractional bandwidths of 1% to 5% are common.

The SNR for direct detection interferometry is derived by considering two interfering fields of comparable power (as compared to the large local oscillator):

$$\left|E_1 e^{i(k_1 x - \omega t)} + E_2 e^{i(k_2 x - \omega t + \varphi)}\right|^2$$

$$E_1 E_2^* e^{i(\Delta k x + \varphi)} + E_1^* E_2 e^{-i(\Delta k x + \varphi)} + |E_1|^2 + |E_2|^2$$

$$|E_1|^2 + |E_2|^2 + 2E_1 E_2^* \, \gamma cos(\Delta k x + \varphi)$$

$$\left[\dot{n}_1 + \dot{n}_2 + 2\sqrt{\dot{n}_1\, \dot{n}_2}\gamma \; cos(\Delta k x + \varphi)\right] T_C$$

$$s = n_1 + n_2 + 2\sqrt{n_1\, n_2}\; \gamma \; cos\varphi$$

$$signal^2 = \langle (s - \bar{s})^2 \rangle = 4\, n_1\, n_2\, \gamma^2 \langle cos^2 \rangle = \; 2\, n_1\, n_2\, \gamma^2$$

$$noise^2 = n_1 + n_2$$

$$SNR_{DD} = \frac{2n_1\, n_2\, \gamma^2}{n_1 + n_2} = n\, \gamma^2$$

for the shot-noise-limited case when the received power at the two apertures is equal. (See Tango and Twiss or Walkup and Goodman for a detailed discussion of direct detection interferometric SNR for measurement of phase and also for amplitude, which has a different low-SNR scaling than measurement of phase.)

This can be expressed in the language of Townes as

$$SNR_{DD} = \gamma^2 \left(\frac{\eta P}{h\nu}\right) \Delta\nu' T_c$$

4. COMPARISON OF HETERODYNE TO DIRECT DETECTION INTERFEROMETRIC SNR

Taking the ratio of SNR_{DD} to $SNR_{zz*,Tc,\Delta\nu}$, (the multichannel, matched bandwidth case), it is straightforward to show that the SNR gain of the direct detection method is

$$Gain_{DD} = \frac{\eta_{DD}}{\eta_{Het}^2} \frac{h\nu}{2P}$$

where again, P is the power per unit bandwidth. The optical efficiency of a heterodyne interferometer can be significantly higher as there is no need for the extensive beam-routing optics. Aggressive values might be η_{Het} = 0.25 compared to η_{DD} = 0.05. However, the direct detection gain under the $M_v = 0$ example above is still 1,600, and increases linearly with increasingly dim targets.

As an example, the SNR for measuring the phase along a visibility-one baseline for a direct detection interferometer with a 2% fractional bandwidth operating at 1550 nm for one atmospheric coherence time of 28 ms and a pair of 1-m apertures is plotted against a 10-GHz single-channel heterodyne interferometer and a 387-channel heterodyne interferometer (with the same effective 2% bandwidth as the direct detection system). A 28-ms coherence time is derived from a $\lambda^{6/5}$ scaling of a typical 8-ms coherence time at 550 nm.

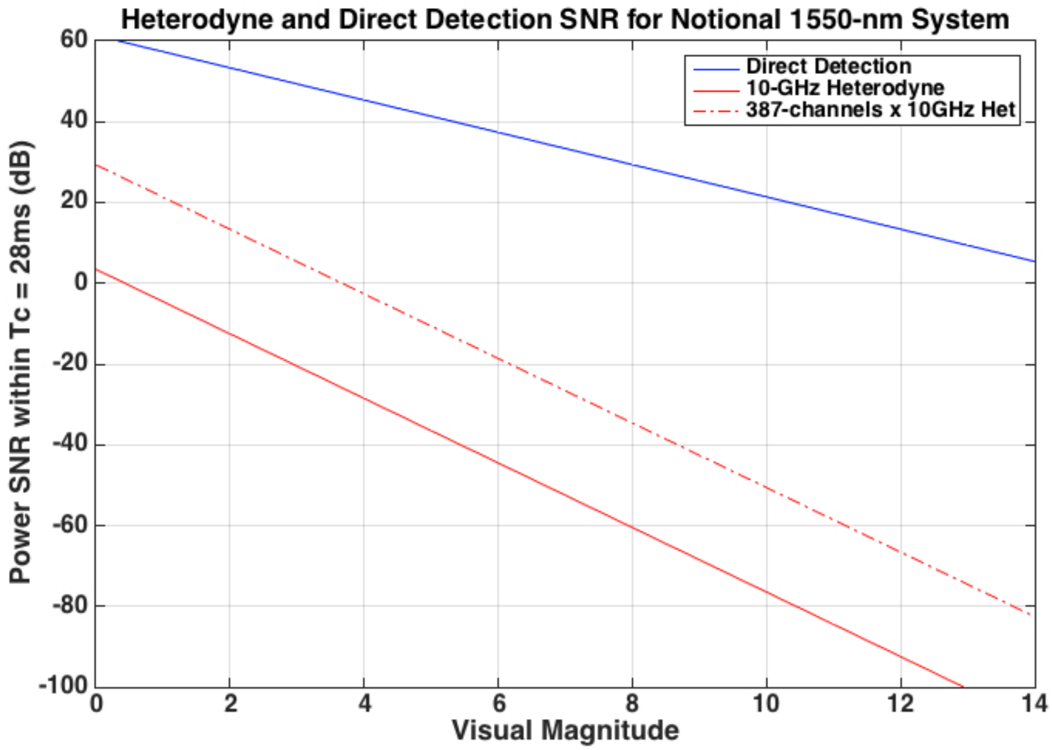

Figure 1. Heterodyne and direct detection SNR for a notional 1550-nm system.

5. HETERODYNE AND DIRECT DETECTION INTERFEROMETRY IN THE MID-WAVE AND LONG-WAVE INFRARED

While there is a significant penalty to the heterodyne approach in the visible through short-wave infrared (SWIR) wavebands where shot-noise-limited detection is possible with direct detection systems, the relationship changes in the mid-wave infrared (MWIR) and LWIR where the direct detection systems are sensitive to thermal noise, due, for example, to radiation from the room-temperature optics. In this case, the SNR for direct detection becomes

$$SNR_{DD} = \frac{2n_1 n_2 \gamma^2}{n_1 + n_2 + n_{kT}} = \frac{2n^2\gamma^2}{2n + n_{kT}}$$

where n_{kT} is defined as

$$n_{kT} = \int_{\Delta\nu'} \frac{dI_{\nu,\Omega}}{d\nu}\, d\nu\; A \cdot FOV^2\, \frac{T_C}{h\nu}$$

where

$$\frac{dI_{\nu,\Omega}}{d\nu} = \frac{2h}{c^2}\,\frac{\nu^3}{\mathrm{e}^{h\nu/kT} - 1}$$

is the Plank blackbody distribution at temperature T, and A•FOV^2 is the etendue of the optical system. The exact temperature and emissivity depend on a detailed stray light analysis, but for a system with optical throughput around 25%, a 300 K blackbody of unity emissivity is conservative and not wildly off. For diffraction-limited single mode detection, the etendue is

$$A \cdot FOV^2 = \frac{\pi^2}{16}\,\lambda^2$$

The Plank distribution near room temperature is well approximated by a simple exponential for wavelengths less than 10 microns:

$$\frac{1}{\mathrm{e}^{h\nu/kT} - 1} \sim \mathrm{e}^{-h\nu/kT}$$

and over fractional bandwidths of the order of 1%, the integral of the Plank function reduces to $\frac{dI_{\nu,\Omega}}{d\nu}\,\Delta\nu'$. Therefore, $n_{kT} \sim (\pi^2/8)\,\Delta\nu' T_C\, exp(-h\nu/kT)$. Using this approximation in the limiting case where the thermal noise dominates the signal, the SNR reduces to

$$SNR_{DD} \sim \frac{2n^2\gamma^2}{1.2\, exp(-h\nu/kT)\,\Delta\nu' T_C} = 1.6\,\gamma^2 \left(\frac{\eta P}{h\nu}\right)^2 \frac{\Delta\nu' T_c}{\exp\,(-h\nu/kT)}$$

which is (with some factors of unity and noting the sign error) the expression in [Townes, eq. 4] for the direct detection SNR. In the thermal-noise-limited case, the gain of direct detection over the (matched bandwidth, many-channel) heterodyne approach is no longer signal dependent, and instead is reduced to

$$Gain_{DD} = 0.8\,\left(\frac{\eta_{DD}}{\eta_{Het}}\right)^2 \exp(h\nu/kT) \sim 4 \text{ at T = 300K}$$

for the optical efficiencies used above (or better, given emissivity ~1 is conservative).

With these relationships, the performance limits of the two approaches can now be compared across the frequency spectrum. We consider a notional interferometer with 1-meter apertures (with adaptive optics assumed in the visible through SWIR range) with a 2% fractional bandwidth per phase measurement (allowing for constructing of a ~50 × 50 pixel scene). As above, $\eta_{Het} = 0.25$ and $\eta_{DD} = 0.05$. A great deal of research has been put into how to efficiently make phase measurements when the SNR is less than unity in a single atmospheric coherence time, but for simplicity, the best possible performance is the Cramér–Rao bound where the number of coherence times required is the inverse of the single-coherence-time SNR times the required variance. (The Cramér–Rao bound is rarely obtained in practice. Closure phase, for example, has a very stressing $1/\mathrm{SNR}^3$ dependence in the number of averages for low SNR.) From this, the Cramér–Rao lower bound on the required measurement time can be obtained. For the discussion of space surveillance, the target is assumed to be a solar-illuminated object of a specified visual magnitude, and the received flux is obtained from the 5780 K solar blackbody (at the top of the atmosphere for simplicity; the transmission to the ground is modest in the useful transmission bands and prohibitive elsewhere).

As the wavelength increases from the MWIR through LWIR, the signal also includes the thermal emission from the target itself. This is approximated as above from the Plank blackbody distribution (at 290 K) with a single-mode etendue, reduced by the object fill factor (because the target is smaller than the single mode field of view, particularly at longer wavelengths). This fill factor is defined,

$$\eta_{Fill} = \left(\frac{D_{Char}}{\lambda R/D_{ap}}\right)^2$$

where D_{Char} is the characteristic length scale of the target, taken as 10 meters for a M_v 10 object, and R is the range. The true effective temperature and length scale of the target will depend on the specifics and operating state of the target, but this provides a rough signal estimate consistent with other analyses. This approximation yields a spectral irradiance of 13 Jy at 10 μm, which is a bit higher than most GEO objects, but M_v 10 represents a very big object.

Figure 2 summarizes this performance for a visibility-1 baseline of a magnitude 10 object and illustrates the enormous advantage direct detection has in the visible through SWIR range. At wavelengths longer than 2 microns, the thermal noise begins to contribute until by 10 microns, the direct detection gain is only a factor of 4. A stated advantage of the heterodyne approach is that, with a multiaperture system, measurements of all N-choose-two baselines can be made without having to split the power, but as the plot shows, this is not as significant a win: a many-aperture direct detection interferometer could be built with a Fizeau beam combiner where light from all apertures is interfered simultaneously on a single focal plane. The power from each aperture does not need to be split; there is simply an SNR penalty equal to half the number of apertures from the additional shot noise. However, in the shot-noise-limited case the direct detection system has many orders of magnitude of advantage, and in the thermal-limited case, the signal shot noise is not significant.

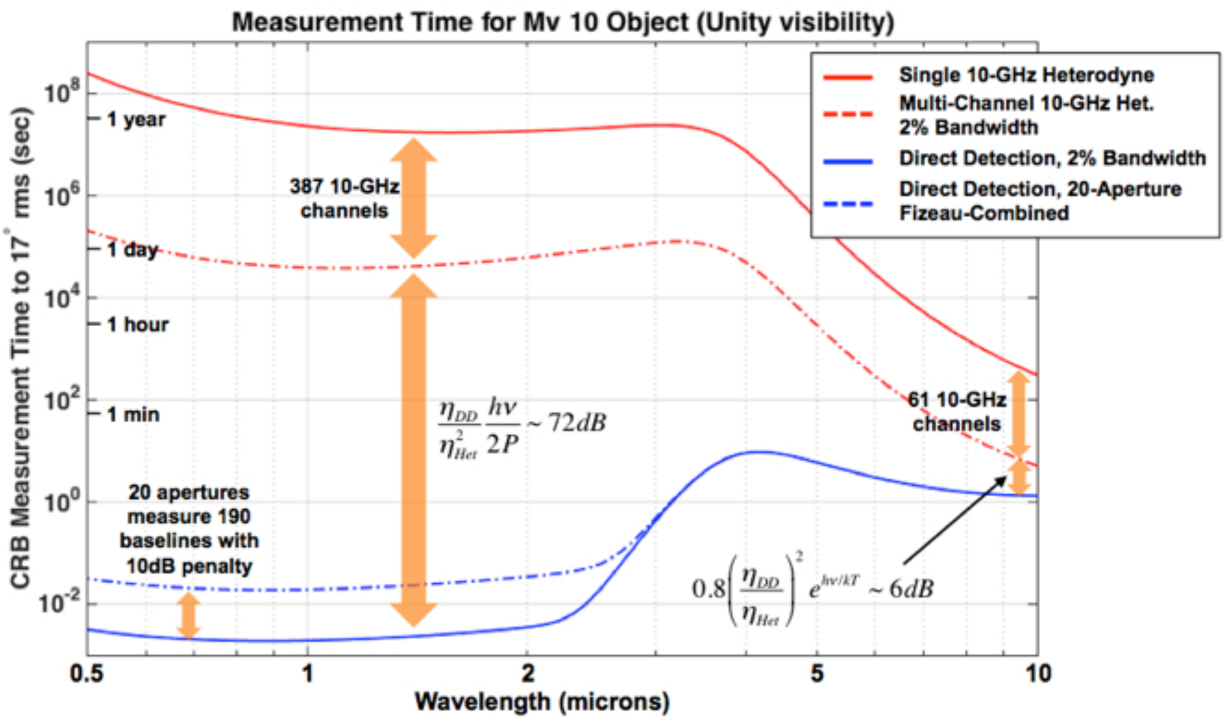

Figure 2. Cramér–Rao lower bound on measurement time for M_v 10 object.

6. SUMMARY

While heterodyne interferometry offers significant system simplification over direct detection implementations, the $SNR \propto P^2$ scaling that comes from 1) the fundamentally small number of photons available from a white light source within the optical/electrical bandwidth and the corresponding coherence time, and 2) the necessity of making a product of two low-SNR measurements in order to obtain the interferometric phase, makes the architecture unsuitable for measurement of dim targets within any practicable measurement time in the visible or NIR wavelength range. In the LWIR near 10 μm, however, the measurement times, while still longer than a comparable direct detection system, become closer to manageable and such a system is worth study. The extremely high data rates of such a system, however, present their own technical challenges.

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14. ABSTRACT

White light heterodyne interferometry is a powerful technique for obtaining high-angular resolution information of astronomical objects, and avoids some of the technical challenges of direct detection interferometry. However, it suffers a significant SNR penalty. This report derives the SNR equations for heterodyne interferometry and compares its performance to a direct detection interferometer in the visible through LWIR wavelength range. Relative performance for imaging deep space, solar-illuminated objects is discussed.

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